Towards Autonomous Smart Sensing Systems

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***Abstract*—Since the 1990's researchers in both academia and industry have been exploring ways to exploit the potential for Wireless Sensor Networks (WSNs) to revolutionize our understanding of - and interaction with - the world around us. WSNs have therefore been a major focus of research over the past 20 years. While WSNs offer a persuasive solution for accurate real-time sensing of the physical world, they are yet to be as ubiquitous as originally predicted when the technology was first envisaged. Technical difficulties exist which have inhibited the anticipated uptake in WSN technologies, the most challenging of these have been identified as system reliability, battery lifetime, maintenance requirements, node size and ease of use. Over the past decade, the Wireless Sensor Networks (WSN) group at the Tyndall National Institute, has been at the forefront of driving the vision of ubiquitously deployed, extended lifetime, low power consumption embedded systems providing information rich data streams wirelessly in (close to) real-time. In this time, the WSN group has developed multiple novel, first of kind, wireless multi-sensor systems and deployed these in the world around us, overcoming the technical challenges associated with ensuring robust and reliable long-term data sets from our environment. This work is focused on investigating and addressing these challenges through the development of the new technologies and system integration methodologies required to facilitate and implement WSNs and validate these in real deployments. Specifically, discussed are the development and deployment of novel WSN systems in the built environment, environmental monitoring and fitness and health monitoring systems.**

The key research challenges identified and discussed are:

a) The development of resource-constrained, extremely low power consumption systems incorporating energy-efficient hardware and software algorithms.

b) The development of highly reliable extremely long duration deployments which through the use of appropriate energy harvesting solutions facilitate (near) zero maintenance sensor networks.

c) The development of low power consumption miniaturized wearable microsystems.

The development of technologies to address these challenges in terms of cost, size, power consumption and reliability which need to be tested and validated in real world deployments of wireless sensing systems is discussed. It is clear that when looking at the scale up of deployments of novel WSNs, that to be successful such systems need to "be invisible, last forever, cost nothing and work out of the box". This paper describes these relevant technologies and associated project demonstrators

Keywords—Energy Harvesting, Smart Systems

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I. Introduction

One of the barriers to wider adoption of battery powered wireless sensor networks is issues around the reliability, logistics and cost of replacing batteries. In large scale deployments these challenges are significant as engineering effort, logistical overheads and costs are incurred to manage the scheduling, stocking and replacement of batteries. Often batteries are in hard to access locations further increasing the labor costs. Managing the battery replacement of a 1,000 unit deployment is not trivial. Battery replacement is often managed through simplified strategies such as; replacing all batteries at a specified time period, (wasting good batteries), replacing when a unit fails (increased down time and data loss), replacing upon alarm detection at specific depletion levels (increased system sophistication). This is supplemented by environmental concerns around battery disposal and the move towards FOG computing on edge devices to enable real time processing and the use of AI techniques [1]. This places placing tougher power requirements on the end node.

II. End Node EH (Energy Harvesting) Powered System

Extending battery life-time with an ultimate aim of autonomous powering of end nodes is gaining more attention in industry [2] and academia. Scavenging even small amounts of ambient energies and converting to electricity can have a significant impact on ultra low power sensing systems. An IoT end node that incorporates EH as part of its powering strategy consists of a number of sub-system blocks as shown in Figure 1. Note that some vibrational energy harvesting systems generate AC voltage, this is not addressed in this system.

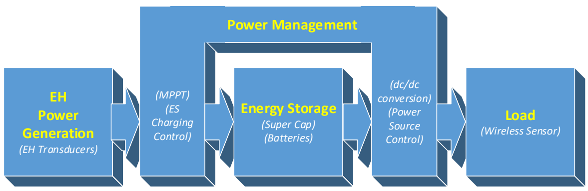

Figure 1: Typical Energy Harvested Power System

The purpose of the Energy Harvested power subsystem is to provide a stable energy source for the load device at acceptable voltage levels with maximum efficiency. Referring to Figure 1, the EH Power Generation block in WSN systems typically converts ambient energies (e.g. light, heat, thermal or RF energy) into electrical power. As the amount of energy generated is typically in the range of tens of microWatts to hundreds of milliWatts, it is very important to ensure maximum energy transfer to the load and energy storage devices by use of maximum power point tracking (MPPT) techniques. In modern integrated End Nodes this function is usually integrated into the Power Management IC (PMIC). As ambient energies is often intermittent, the load device is rarely powered directly from the transducer. Energy is stored in either a super capacitor or a secondary battery. Another function of the power management block is to control the charging of these storage devices. In some systems a primary battery forms part of the energy storage block where the power management function controls switching between primary and secondary sources. Finally the load is connected to the energy storage device via boost or buck converters to ensure a suitable voltage with maximum efficiency.

A. EH Power Generation

TABLE I. below shows the power that is typically generated by Energy Harvesting transducers that are commonly used IoT end nodes [3].

TABLE I. TYPICAL ENERGY HARVESTED SOURCES

Energy Harvesting Sources		
Energy Source	***Type***	***Typical Power***
Outdoor solar light	Natural	100 mW/cm2 (outdoor)
Indoor office light	Artificial/natural	100 µW/cm2 (artificial light)–10 mW/cm2 (filtered solar light)
Ambient RF	Artificial	0.001µW/cm2(WiFi)–0.1µW/cm2 (GSM)
Thermoelectric	Artificial	60 µW/cm2
Vibration	Artificial	4 µW/cm3 (human motion) 800 µW/cm3 (machines)

B. Power Consumption (Load)

A typical Wireless Sensor end node has a number of components: the Sensor, the Radio Transceiver and the Microprocessor (MCU). Figure 2 below shows a typical configuration of an end node. The microprocessor controls the acquisition of data from the sensor either through standard digital interfaces such as I2C ,SPI or analogue interface where some sort of conditioning circuit is usually required to present the signal to the ADC built into the MCU.

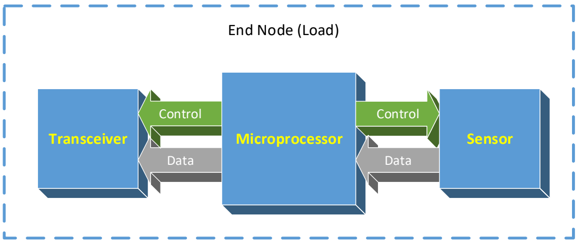

Figure 2: End Node (Load) Block Diagram

The MCU also controls the transceiver to enable sensed data to be transmitted back to a gateway. Therefore, the microprocessor is the principal component that influences power consumption in the end node. Careful consideration needs to be made in relation to setting appropriate low power modes within the microprocessor and the transceiver as well as keeping all sensors turned off when not used (duty cycling).

TABLE II. TYPICAL IOT POWER CONSUMPTION PROFILE

	Tx Power	**Rx Power**	**Sleep Power**
BLE	31.7mW	29mW	3.24uW
802.15.4	24.11mW	19.26mW	4.32uW
802.11.ah	400mW	130mW	7.5uW
802.11b PSM	699.6mW	170mW	9.45mW
LoRa	419.6mW	44.06mW	4.32uW
SIGFOX	147mW	39mW	4.32uW

A detailed analysis of energy consumption of transceivers is highly complex and beyond the scope of this paper as it is dependant on a number of paramters related to, duty cycle and operation modes such as Sleep, Idle, Rx and Tx that are all unique to a given protocol and application. A table of typical IoT protocols is given in TABLE II. derived from [4]. The authors of this paper analysed a number of SoCs that included a microprocessor and radio module. The table below is derived from this paper and shows the typical power consumption for some commonly used protocols in IoT for a number of typical power states. TABLE III. [5], is a list of typical sensor power consumption.

TABLE III. TYPICAL ANALOG SENSOR POWER CONSUMPTION [3]

Analog Sensors	**Power**
Pressure	1 – 20mW
Acceleration	3 – 35mW
Temperature	378 – 600uW
Humidity	1 – 3mW
Gas	< 800mW
Displacement	< 1mW

A crucial aspect of power consumption is the duty cycle employed by the system. Reducing the average load power consumption gives us the best chance of powering the device from energy harvested sources. Below are two examples to ilustrate the effect duty cycling has on power consumption.

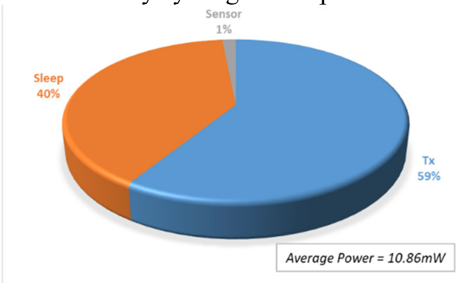

Figure 3: Power Consumption Transmitting Data every 30 seconds

Figure 3 shows a simplified analysis of power consumption of an end node that is transmitting 10 byte packets using 802.15.4 protocol every 30 seconds at 10Kbps. The figures for typical 802.15.4 transcievers were used from TABLE III. above. The sensor was modelled using a HTU20D humidity and temperature sensor that consumes 450uW and has a measurement time of 10ms. From Figure 3, the average power consumed is dominated by the radio transmitting data and is aproximately 10uW.

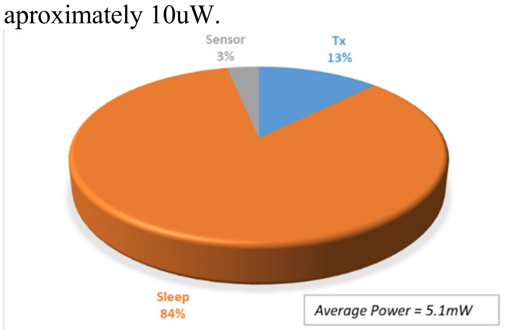

Figure 4: Power Consumption transmitting data every 300 seconds

Figure 4 shows how the distribution changes when we increase the data transmission to every 300 seconds (5 minutes). In this case the sleep current dominates the overal power consumption with a total consumption of 5uW.

These examples show the many complex trade-offs between, radio, microprocessor and sensing hardware. Together with selection of protocol and data transmission characteristics that has to be made to realise the minimum power consumption for the end node.

C. Energy Storage

Energy Harvesting systems require some sort of energy storage element to store for later usage when there is an excess being generated and to supply power when there is not enough generated. In general, there are two forms of energy storage commonly used, one is super capacitor, the other being battery. Many applications use both forms of energy storage.

The selection of storage technologies depends on the application, as super capacitors are more suited to frequent short duration, charge / recharge cycles, supplying short bursts of energy quickly, as they have higher power density compared to batteries. They are not suited to long term storage as leakage current (self-discharge) is high compared to battery technology. With their lower ESR (effective series resistance) supercaps can supply energy faster than batteries (but only for short durations). Batteries only have a limited number of charge cycles, typically in the region of a few hundred, compared to hundreds of thousands for capacitors. However, batteries exhibits higher energy density and can hold charge for long periods and so are more suited to applications that consume small amounts of power over a long period. The table below [7] summarises and compares the main features.

TABLE IV. BATTERY TECHNOLOGY COMPARISON

Feature	Li-ion Battery	Super Capacitor
Specific Energy (Wh/kg)	8 - 600	1 - 5
Specific Power (W/kg)	100 - 3000	>4000
Charge Method	Complex	Simple
No of recharges)	150 - 1500	>100,000
Life (years)	5 - 10	10 - 15
Charge / discharge over time	1 to 10 hours	msec to secs

D. Power Management

As can be seen from Figure 1 the Power Management block is the heart of the Energy Harvesting system. This block ties together the Energy Source, Energy Storage and Load device to ensure that the power generated is efficiently delivered to the load. To achieve this the power management block performs a number of critical functions as shown in the functional diagram in Figure 5 below.

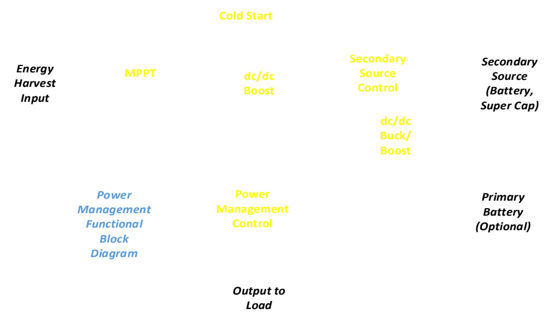

Figure 5: Power Management Functional Diagram

The Maximum Power Point Tracking (MPPT) block ensures that the optimum load impedance is presented to the energy harvesting transducer so that maximum power transfer takes place. There are a number of techniques to implement this, Gupta and Saxena [6] describe the most common methods. Selection of the technique requires careful consideration of the application. In low power systems where micro watts are important we find that techniques such as Perturb and Observe, although very precise in tracking the maximum power point, require power to function that negates the performance gains. In low power systems, techniques such as Fractional Open Circuit Voltage (FOCV) or Fractional Short Circuit Current (FSCC), although less precise in tracking the maximum power point, often prove better overall as they require less power to function. Indeed perturb and observe [6] is often best suited to high power grid connected systems where milli-watts of power for the circuit to function is insignificant for the application. All energy harvesting systems require energy storage. The power management circuit therefore needs to condition the harvested power to charge either batteries or supercaps. Charging for certain types of batteries can be complex and so the secondary source control block controls the charging of these devices. To source power from super capacitors including buck/boost circuits in this block, ensures the maximum amount of power can be extracted further increasing the efficiency of the system. As can be seen from Figure 5 there are potentially a number of sources available to the load for powering namely the primary battery, secondary battery, super capacitor and energy harvesting transducer. This requires a control circuit (power management control) algorithm to ensure that the load is powered in the optimum way without interruption to supply.Self powering from the harvested energy ensures optimum efficiency of the power management block. This requires a function called cold start, which enables the device to power up from minimal power and voltage levels. State of the art devices are able to cold start at 380mV and 3uW of power [ref epeas AEM 190941]. This is essential for systems that have or low-power (<10uW) energy harvesting capability.

E. EH Power System Design and Optimisation

Optimising an Energy Harvested powered wireless sensor requires a series of complex trade-offs and system level device balancing/sizing between, Energy Storage, Energy Harvester Transducers, Power Management and the Wireless sensing unit (load). Tyndall has created innovative and easy to use deployment tools to assist the designer in making these trade-offs under H2020 EU funded projectsReC02ST. Tyndall's simulation tool enables the systems integrator to easily trade off all the components of a complete energy harvesting power system, independent of component vendor. In addition this tool is also useful to the component level designer to observe the effect of their component on the overall system. The user selects each component part of the system. One can select from one of the embedded library parts, i.e. models developed by Tyndall. Alternatively the user can undertake their own characterisation and add to the library. The simulation will provides the user with the expected battery life-time with or without energy harvested power. The thresholds at which the simulation switches the battery in and out of circuit is user defined and is determined by the supercap voltage. Figure 6 shows a typical output of the tool. The blue line is the super capacitor voltage that is plotted against time. For the plot below the simulation is set with an indoor PV cell and one can observe the diurnal charge and depletion cycle.

Figure 6: Energy Harvesting Simulation Tool Output

III. Deployed EH End Nodes

A number of systems have been deployed by Tyndall National Institute that demonstrates situations where Energy Harvested powered IoT End nodes have been successfully deployed. This section outlines these systems their impact.

A. BLE Asset Tracking System with EH power assistance

As part of the Factories of the Future COMPOSITION project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 723145. Tyndall developed a retrofitted Energy Harvesting system to extend the battery life of BLE beacons by 110% in an off the shelf asset tracking system [9].

The asset tracking system deployed in COMPOSITION was a proximity based system and deployed on the manufacturing floor of a large medical devices company. The BLE receivers are attached to equipment that needs to be located (known as Tags). The location of these Tags is determined comparing signal strength measurements from beacons that are at known locations. The tag assumes it is closest to the beacon of the largest signal strength. The beacons are battery powered and located in hard to reach locations on the ceiling. Extending the battery life of these beacons reduces maintenance schedules and yields a significant cost saving. The BLE asset tracking signal used was an off the shelf system named AirFinder supplied by Link Labs Inc. The beacons are supplied by 2 AA batteries and had a typical life time of approximately 260 days. Figure 7 below shows the system that was developed by Tyndall to extend the battery life to approximately 560 days based on split shift system where the lights are on for 16 hours each day and no working during the weekends. The system consists of a PV cell Energy Harvester, a Super Capacitor Energy storage element and a Tyndall power management board that controls the switching between power sources as well as the Maximum Power Point Tracking (MPPT) circuit. This circuit is a Tyndall developed Fractional Voltage Open Circuit architecture optimised for low energy levels [8]. The BLE beacon transmits a unique identifier through transmission of standard advertising packets every 45ms. The power profile is shown below in Figure 8. The average power consumed is 1.44mW

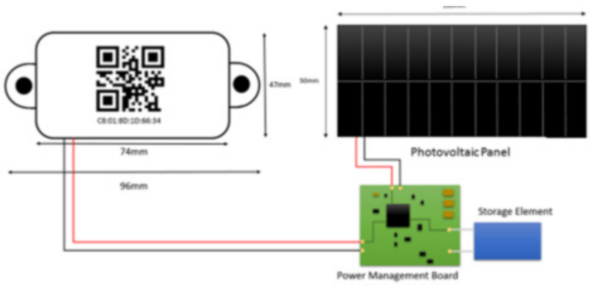

Figure 7: PV Energy Harvesting System Block Diagram

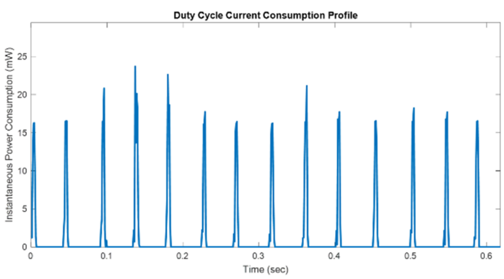

Figure 8: BLE Beacon power profile

The lighting conditions on the manufacturing floor were measured at 1200 Lux. Using the Tyndall power management circuits and a AM1816 PV panel which measures 50cm2 (53.3 x 94.7mm) we were able to generate up to 1.46mW in full lighting conditions. Figure 9 below is a simulation plot that shows in blue the super capacitor voltage and in red whether the system is being supplied from the energy harvesting system (1) or battery (0), over a three week period. From the plot one can see that the super cap voltage depletes very quickly when there is no light available. The threshold for switching to the battery is about 2.5V. From this simulation battery lifetime was extended by about 110%. Measurements from the deployment are ongoing.

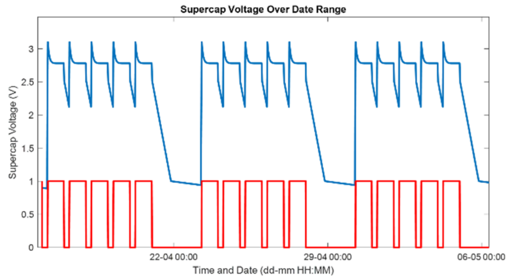

Figure 9: Energy Harvesting Simulation

B. EH powered multi-Sensor WiFi end Node

MOEEBIUS is an EU H2020 funded project that optimises the modelling of energy efficiency in buildings. New tools and methodologies to reduce the gap between predicted and actual energy performances at the level of buildings and blocks of buildings are in continuous development in academic and industry organizations. The development of Wireless Sensor Networking (WSN) technology plays a core role in this field since their development enables the monitoring and control of application within the building environment. As part of this project, environmental conditions needed to be measured to help develop and validate these models. Tyndall developed a Wi-Fi connected wireless sensor platform shown in Figure 10 that monitored a large number of environmental parameters.

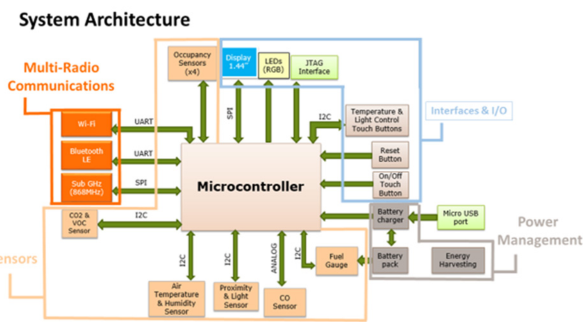

Figure 10: MOEEBIUS Wireless Sensor System Diagram

The device (NOD) incorporates a 32-bit ARM-Cortex microcontroller, a variety of sensors to monitor the ambient conditions – luminance, temperature, humidity, air quality - and multiple radio interfaces - WiFi/Bluetooth LE/868MHz. A significant challenge from a powering perspective was that this development used Wi-Fi___33 as its method of communication as well as using gas sensors as shown in TABLE II. and TABLE III. These are both power hungry elements for IoT devices.

To reduce the power consumption of the Wireless Sensor the design optimized the control of the sensors by switching to low power modes as often as possible. To extend the life of the battery an Energy Harvesting System was developed as shown in Figure 11. This design is centered around MPPT circuits that use a Fraction Voltage Open Circuit technique. The maximum power point is tracked by comparing the fractional open circuit voltage on Cfocv with the voltage fixed between R3 and R4. This controls the charging of the super capacitor Cout by switching on and off depending on threshold levels. The Oscillator block (OSC) momentarily breaks the connection between PV and MPPT to replenish Cfocv. The output control block (O/P CTRL) function is to switch the output to the energy harvested power stored in the supercap when there is enough energy available, thus reducing the drainage on the battery (EXT. BAT). It extended battery life by 40% with scope to extend indefinitely if power consumption could be reduced to 420uW.

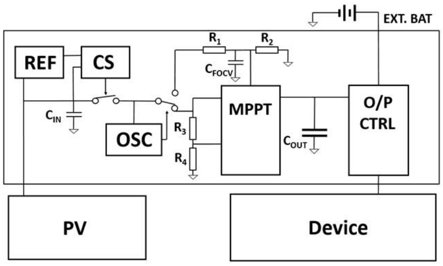

Figure 11: MOEEBIUS Energy Harvesting Sub-System

C. Multi-Source Energy for Monitoring Applications

In rotating machinery, gear and bearing are critically important components. They are required to operate with high reliability for extended period of time in harsh environmental conditions [10]. Unexpected Faults (UFs) of the gear and bearing may lead to damages of entire machine.These Unexpected Faults can be identified through the characterisation of Acoustic Emissions (AE) and Fourier transform analysis of the acoustic signals. Wireless technology to monitor and identify Unexpected Faults was developed as part of the MOSYCOUSIS Project [11]. However, a bottleneck of WSN development is the limited battery energy. The 0.5 milliwatts ultra-low power WSN system can only achieve 6-month battery lifetime when powered from 1000mAh battery in optimal condition. The task to regularly replace battery can become expensive when the number of WSN motes is large and even impossible when the mote is placed in difficult-to-access locations. The MOSYCOUSIS project introduced a vibration/thermoelectric/light powered wireless sensor module based acoustic emission monitoring system for rotating machinery fault detection application. Fig.12 illustrates the application of this proposed system in gas compressor monitoring.

TABLE V. POWER CONSUMPTION OF AE MOTE (TS : SLEEP MODE TIME)

AE Power Consumption	Power (mW)	Time (Sec)	Energy (mJ)
Sleep Mode	0.047	60.00	2.820
Data ACQ (3 AE Sensors)	188.1	0.020	3.760
Data FRFT & Compression	76.26	0.920	70.16
DSP-Algorithm	86.16	0.210	18.09
RF Transmission	61.38	0.220	13.50
Total (1min TS)	1.760	61.37	108.3
Total (3 mins TS)	0.620	181.3	113.9
Total (10 mins TS)	0.220	601.3	133.7

Low power consumption of data processing and transmission is a main challenge in the design of AE WSN system. The MCU based device consumes 80-180mW power during "active" mode and 50µW "sleep" mode power. The power consumption of AE WSN mote is summarized in TABLE V. Since the harvested power from ambient environment is at 1mW level, the AE WSN system is programmed to perform duty cycling operation (periodic active-sleep-active cycles) in order to minimize average power consumption. On average, the active mode time is approximately 1.37 seconds followed by the sleep mode time of 1 to 10 minutes in the tests. The average power consumption ranges from 0.22mW to 1.76mW subject to the operational duty cycles.

Multi modal energy harvesting technology (Thermal and Vibration) was integrated in to the AE monitoring system and the feasibility of powering AE WSN mote entirely from energy harvesting investigated. In deployment conditions on an air compressor, the proposed power management circuit shows that it can harvest 3.37mW from wasted heat and 1.56mW from machine vibration, then store the energy in super-capacitor type energy storage unit. The hybrid energy harvesting subsystem generates 4.93mW when the air compressor is operational. Based on the AE system power consumption characterizations, the harvested power is sufficient to perform AE fault detection every 20 seconds and achieves power autonomy in the air compressor experiments.

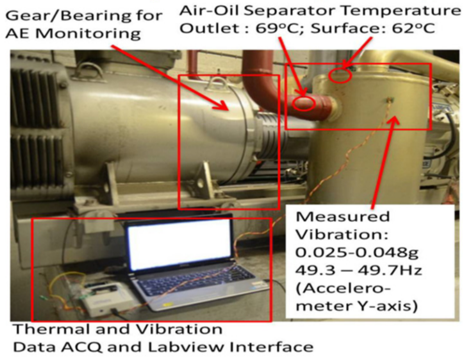

Figure 12: Energy Harvester Powered AE System Deployment

D. Batteryless, Contactless NFC sensing

The APACHE (Active & intelligent Packaging materials and display cases as a tool for preventive conservation of Cultural Heritage) project is a H2020 project focused on the reduction of costs for maintaining and controlling constant climate conditions [12]. In the Apache project the team developed a battery-less, long shelf life, low-cost sensor transponder for use in monitoring the temperature and humidity conditions inside cardboard artefact storage boxes. NFC is a short-range wireless communication technology that has evolved from existing contactless identification technologies [13]. NFC uses magnetic coupling between two loop antennas located within each other's proximity and vicinity. NFC has shown growth in the past few years due to the incorporation of NFC readers into smartphones and gaining significance in Internet of Things (IoT). The APACHE solution block diagram and system architecture are shown in Fig Figure 13 0. The NFC radio analog front end (AFE) consists of an RF interface and the energy harvesting circuitry which will connect to the loop antenna. The energy harvester harvests energy from the magnetic field (H-Field) of an NFC-V enabled smartphone with the help of internal rectifier and capacitor.

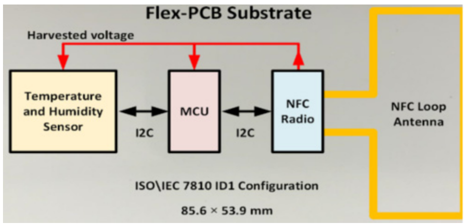

Figure 13: Proposed NFC temperature/humidity sensor.

The harvested voltage is regulated using a low dropout regulator and used to power up the Ultra-low-power microcontroller (MCU), temperature and humidity sensor. When the magnetic field strength from the reader is sufficient, the harvested energy will be available to power up the MCU, NFC radio, temperature and humidity sensor.

E. Power Management IC MISCHIEF

As previously discussed a critical part of the Energy Harvesting Power system is the Power Management function. Tyndall has developed an Intelligent multi source Ultra Low Power PMIC under the Enterprise Ireland funded MISCHIEF program. TABLE VI. below shows a comparison of the key low power specifications between MISCHIEF and other leading commercial PMICs. The PMIC design incorporates a number of ultra low power technologies to be able to operate at lower energy inputs, thus increasing the overall energy harvesting power source efficiencies.

TABLE VI. MISCHIEF PMIC COMPARISON

Parameter	MISCHIEF	Best Commercial
Efficiency	90-95%>10uW 75-90%<10uW	Typ 2-5% lower Most inoperable
Min I/P Voltage	20mV	50mV
Min ambient energy usable	<1uW	>3uW
Quiescent current	<200nA	340nA
Digital Interfacing	Yes	No

The MISCHIEF PMIC provides all of the critical PMIC functions but has been designed to operate at very low power and voltage levels that are generated from real life ambient energies from multiple sources. The PMIC incorporates multiple energy harvester interfaces, cold start, ultra low quiescent current, MPPT, energy storage management supporting super capacitors and batteries, highly efficient buck-boost converters over a broad range of input and output voltages and power levels and various load power management functions. One of the unique aspects of the design is the digital interfacing capability. This will enable the PMIC to form an intelligent power control system within the end node, controlled by the MCU facilitating interaction with the load device (wireless sensor) to dynamically change sensing and transmission parameters, to conserve power based on contextual awareness.

IV. CONCLUSIONS & RECOMMENDATIONS

The proliferation of automation and optimisation in electronic systems is driving the need for sensed data. Barriers to wider adoption are cost and autonomous power of these devices. This is because increasingly the expectation is that sensed information should come for free, as the value of the data is in its analysis not its collection. Integrating energy harvesting to autonomously power sensors is a huge challenge as gaps still exist between the power that can be generated and the power required to operate wireless sensors. However, with the research being conducted that is described in this paper this gap is closing.

Autonomous operation of a wireless sensor requires a highly complex power system to be optimised, from the generator, to storage, to the power management through to the load device. Although the designer can select the lowest power devices to reach these objectives, without proper control and power management strategies in place the overall system power performance can be compromised. This paper describes a suite of tools and technologies that with continued development will help enable autonomously powered Wireless Sensors.To enable autonomous operation all facets of the WSN system must be optimised with power as one of its goals. This requires further development of low power semi-conductor technology. Power Management ICs optimised for ambient power energy harvesting transducers. Development of Artificial Intelligence algorithms as part of an Edge computing strategy to optimise system power consumption. New protocols that are adaptive to power requirements as well as throughput. Finally these sub system blocks must be integrated together carefully to ensure all the benefits are leveraged to their full extent.

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